Early Journal Content on JSTOR, Free to Anyone in the World

This article is one of nearly 500,000 scholarly works digitized and made freely available to everyone in the world by JSTOR.

Known as the Early Journal Content, this set of works include research articles, news, letters, and other writings published in more than 200 of the oldest leading academic journals. The works date from the mid-seventeenth to the early twentieth centuries.

We encourage people to read and share the Early Journal Content openly and to tell others that this resource exists. People may post this content online or redistribute in any way for non-commercial purposes.

Read more about Early Journal Content at http://about.jstor.org/participate-jstor/individuals/early-journal-content.

JSTOR is a digital library of academic journals, books, and primary source objects. JSTOR helps people discover, use, and build upon a wide range of content through a powerful research and teaching platform, and preserves this content for future generations. JSTOR is part of ITHAKA, a not-for-profit organization that also includes Ithaka S+R and Portico. For more information about JSTOR, please contact support@jstor.org.

PUBLICATIONS
OF THE
Astronomical Society of the Pacific.

Vol. XXXIII. San Francisco, California, December, 1921 No. 196

THE PROPERTIES OF MATTER AS ILLUSTRATED BY THE STARS[1]

BY HENRY NORRIS RUSSELL

When Professor Aitken and Dr. Evermann did me the honor to ask me to speak before you today, I chose a large subject. I hope that you will not conclude that my motive was that of the inexperienced preacher who always took a whole chapter for his text, so that "if he was persecuted in one city, he might flee to another."

But let me proceed to my topic, saying only that most of what I will say deals with other men's work, and but little with my own.

Among the many properties of matter which are illustrated by the stars, I shall confine myself to those which are primarily properties of atoms, for there has been an amazing development in the last decade or two, both in our knowledge of the stars and in that of atoms, and the two are becoming more and more intimately associated, as I hope to show you this afternoon.

Let us begin with a bit of history. Rather more than fifty years ago, we first found ourselves in possession of a means of investigating the properties of matter in distant regions of the universe, by means of the spectroscope. We all know how the absorption in the atmosphere of the stars of the light which comes from deeper down, produces the dark lines in the spectra, and that each individual constituent of the atmosphere, whether element or compound, absorbs its own distinctive lines—the same which it would emit if its vapor were raised to a high enough temperature.

The pioneer work of the sixties showed at once that many of the familiar terrestrial elements—hydrogen, iron, sodium, calcium, and so on—were present in the atmospheres of the Sun and the stars. Later investigations have revealed the presence of about fifty of the terrestrial elements in the Sun, and of many in the stars, and practically all the lines in these spectra (except the faintest, which have not yet been fully studied) are now identified with "known lines" which can be produced in the laboratory.

---

[1] An address delivered in Wheeler Hall, Berkeley, August 5, 1921, before the Pacific Division of the American Association for the Advancement of Science.

One episode in this story is too shining to pass by. In 1871 Lockyer observed a bright yellow line in the spectrum of the Sun's outer atmosphere (the chromophere) during a solar eclipse, and found that, with proper instrumental means, it could be seen at any time. It was not far from the sodium lines, but could not be identified with any line of any known substance. He concluded therefore that it belonged to some element present in the Sun, but unknown on the Earth, and called this *helium*. As the yellow line in the solar chromophere rose very high, like those of hydrogen, he concluded that helium was probably a gas of low density. Twenty-five years later this solar element was at last run to Earth—being found in the gases given out on dissolving certain uranium minerals in acid—and when its spectrum was investigated, the yellow line, and a considerable number of other lines, were found, coinciding with lines observed in the Sun's atmosphere, and in stars like those in the belt of *Orion*. These are only the opening chapters of the most fascinating of the romances of physical science, but we cannot pursue the tale further, pointing only our moral that this form of matter was discovered in the nearest of the stars—the Sun—and certain of its properties correctly deduced, before it was ever known on our own planet.

But long before this story had reached its second chapter, the main lesson of the stellar spectra was clear. The elements which we know on the Earth are to be found all thru the visible universe. Matter is of the same ultimate constitution everywhere. We are so familiar with this great conception of the uniformity of nature that we hardly realize how great a step in advance it was, fifty years ago, and how much it meant, not only to science, but to philosophy. I think that no one has expressed the matter better than the poet Stedman, in lines which deserve to be more widely known than they are—

"White orbs like angels pass
Before the triple glass
  That we may read the record of each flame,
Of spectral line and line
The legendry divine
  Proclaiming them the same, and still the same,
The atoms that we knew before,
Of which ourselves are made: dust, and no more."

Until ten years or so ago that was all we knew: but now we have good reason to be sure that the atoms are the same everywhere because they have to be so. They are no arbitrary, indivisible entities, but are structures,—and we have a pretty fair idea of the general nature of this structure.

The investigations of Rutherford and others have shown that in all probability, an atom is a complicated structure composed of electrons, all alike, and carrying negative electrical charges, grouped about a central nucleus which is very small, and has a positive charge equal to the sum of all those of the electrons—so that the atom as a whole is electrically neutral. For any given nuclear charge, the electrons arrange themselves automatically in a definite pattern, of which we can now glimpse the fundamental lines, tho the details remain to be worked out. The electrons appear to be arranged in successive concentric shells or layers about the nucleus—the first shell containing only two, the next two eight apiece, the next two eighteen each, and the next one thirty-two. If the number of electrons is insufficient for all this scheme, the inner shells will be completed, leaving the outer one incomplete. Lewis and Langmuir have shown that this hypothesis accounts for the chemical properties of the atoms in an extraordinary way. These, and also the character of the spectrum, depend almost entirely upon the outer incomplete shell of electrons—the inner parts of the atoms having to do with such things as the emission of X-rays.

This new conception of the atom has led to a deeper understanding of the processes which are involved in the emission and absorption of light, and this again to an interpretation of our astrophysical observations, which will be the main topic of my address.

Since first the spectra of the stars were observed it has been recognized that they can be grouped into a relatively small number of classes. The photographic studies of tens of thousands of stellar spectra by Pickering and his associates at Harvard—notably by Mrs. Fleming and Miss Cannon—showed that 99½ per cent of them can be arranged in a definite sequence. We may pick out a set of stars whose spectra are exactly alike, then a second set whose spectra differ to a barely perceptible degree from the first, and so on, step by step, till we come finally to spectra which are entirely unlike those with which we started, but clearly connected with them thru the intervening types. A conspicuous change of color is definitely connected with this spectral sequence. We begin with very white stars, showing mainly the lines of hydrogen and helium, pass to yellower ones, which, like the Sun, show thousands of metallic lines, and end with red stars, in whose spectra appear bands due to the presence of certain chemical compounds—(such as titanium oxide).

It was once believed that these differences arose from differences in the chemical composition of the stars—that the white stars contained abundant helium and no metals, and the yellow stars plenty of metals but no helium. But nowadays we have a better interpretation. Take any element—iron, for example. Start its vapor shining at as low a temperature as possible in a suitably designed electric furnace, and turn your spectroscope upon the light which it emits. You will find a certain number of lines. Heat the furnace hotter. These lines brighten up, and more lines appear, which were not there at all when the temperature was lower. Pass to the arc between iron poles. Still more lines come up: And we get a new and important crop when we go on to the high-tension spark between iron wires: for here, tho the whole supply of energy is not very great, we are putting in a great deal per atom of the luminous vapor.

We can now understand what is meant by furnace lines, arc lines, and spark lines (or enhanced lines, as the last are often called). Fortified with this knowledge we find that, in the red stars, the flame lines of the metals are predominant. Yellow stars, like the Sun, show them, but also the arc lines, while the white stars exhibit the enhanced lines. This shows that we are dealing with increasing excitation of the atoms the whiter the stars are; and it is a very remarkable fact that we can reproduce, with the relatively feeble means at our command in the laboratories almost all the states of excitation of atoms which nature, working on a tremendous scale, brings about in the atmospheres of the stars.

So much has been known for years; but very recently we have been able to substitute for this empirical knowledge a rational theory. This new idea of what happens when an atom radiates light we owe primarily to Bohr and Sommerfeld.

Consider an atom, with the electrons in its outer shell. If a suitable force is applied, one of these electrons can be pulled off, leaving the rest of the atom with a positive charge. This process is called ionization. But it appears that it does not happen at one fell swoop. Between the original, normal, state of this electron, and the final state of complete separation, there are a multitude of other possible states, in each of which the electron can remain for a long time (measured in units suitable to the problem).

These states correspond perhaps to different orbits in which the electron can move around the residue of the atom. At any rate they involve the imparting to the electron of different amounts of energy, and they can therefore be arranged in sequences of higher and lower energy content.

When the electron shifts from one of these states to another light is emitted (if the change is from a "higher" to a "lower" level) or absorbed (if the change is in the opposite direction, and demands that energy be put with the atom in order to bring it about). This light, whether emitted or absorbed, takes the form of vibrations of a definite frequency, corresponding to a sharp line in the spectrum: and the number of these vibrations per second is exactly proportional to the amount of energy required to produce the change from the initial to the final state of the electron. Why this should be, no one knows at all—it involves the famous quantum theory which is regarded by its keenest students as the most difficult of all the problems of physical science. But the fact has been placed beyond reasonable doubt by the work of the past ten years. If we start with an atom in its normal state (corresponding to the smallest energy content) the electron may be raised by absorption of energy from outside to any one of a long series of higher states. To each of these changes corresponds a line in the spectrum, and these lines are arranged in a series (getting closer together toward a limit in the violet or ultra-violet) which is called the "principal series". If we start with an atom in which the electron is already one step above the bottom, shifting it to higher levels produces other lines which can be arranged in two "subordinate series", and still other absorption lines correspond to the raising of the electron from positions two or more steps above the bottom.

At the limit this electron can be taken clean away from the atom, ionizing it. But it is then possible to remove a second, (except in the case of hydrogen, where there is only one electron in the atom) and this second ionization also can take place in a great number of steps, similar to the first, and giving lines belonging to principal and subordinate series. In general, it takes about twice as much work to remove the second electron as the first. The corresponding spectral lines will therefore lie much farther towards the ultra-violet—usually, alas, so far that they are obscured in the heavenly bodies by the Earth's atmosphere, which is entirely opaque for light only a little shorter in wave-length than the limit to which our eyes can see under favorable conditions.

We can measure the amount of work which is required to pull an electron out of an atom of a given gas, by setting up a vacuum tube in which a stream of electrons is set going by the action of a known drop in voltage, and then passed into a chamber containing the gas at a low pressure. For a small voltage drop and slowly moving electrons, nothing happens. But, with faster electrons, the gas begins to emit light. The collisions are violent enough to knock electrons within the atoms of gas from the normal position to the next higher step, and as they fall back again, light of the appropriate wave-length is given off. For a higher speed of the electron stream, the collisions become violent enough to knock an electron clear out of the atoms which are hit, and ionize them. At this point the gas begins to conduct electricity, and all the lines appear. The voltage which is just sufficient to get up this electron speed is called the ionization potential, and measures the difficulty of getting an electron out of the atom.

The application of these principles to the Sun and stars—which bids fair to open up a field of very great importance—was first made, a year or so ago, by Dr. Megh Nad Saha, an East Indian, who is a Professor in the University of Calcutta. Following his lead, we may learn a deal about what is happening in the Sun and stars.

Furnace lines (speaking in general) correspond to the shifting of an electron in the atom from its normal or lowest position to the position a step or two higher: arc lines, to shifts from one of these higher positions to a still higher stage: while enhanced lines are produced only by an atom which has lost one electron altogether and is in process of having the second loosened.

Let us apply this to the spectrum of the Sun, and of sun-spots. The temperature of the Sun's atmosphere is about 6000° Centigrade that of the spots probably about 4000°. In either case, the atoms of the gases in the solar atmosphere will collide violently, and suffer internal disturbances in consequence; but at the higher temperature these disturbances will be more violent.

Take now an element easy to ionize, like sodium. On the Sun's surface, at 6000°, calculation shows that the internal disturbance of the atoms will be so great that most of them will be ionized. In the spots, the proportion will be smaller. Now the neutral sodium atom alone can give the familiar spectral lines of sodium—the ionized atoms giving lines in the far ultra-violet. However, in the spots, where the proportion of sodium atoms which are not ionized must be greater, the sodium lines should be stronger, and so they are, all of them.

Potassium, which is easier to ionize, shows the same effect to a more marked extent. The rare alkali metal rubidium is still easier to ionize. Its lines do not appear in the solar spectrum at all. This suggests that in the solar atmosphere it is completely ionized, leaving practically no atoms in a condition to absorb the lines that we are looking for, but that in the spots there may be enough of the neutral atoms to produce the lines. This was predicted by Saha, and when I went to Mount Wilson I looked the lines up on some beautiful photographs which had been made by Mr. Brackett—and found the lines in the spot spectrum, just as had been predicted, thereby adding a new element to the rest of those known to be present in the Sun.

Calcium can lose two electrons fairly easily. In the process of removing the first, the furnace and arc lines are absorbed, while the removal of the second gives the enhanced lines. The first step of this latter process produces the H and K lines which are the strongest in the solar spectrum—whether on the disk at large or in the spots—which is in agreement with the fact that most of the calcium must be ionized in both cases. The flame and arc lines of calcium are strengthened in the spots (where there are more atoms in a state to absorb them). It is of great interest to note that those lines which correspond to a shift of the electron from the normal state to the next step are the most strengthened in the spots. Next come those which are produced by a shift of an electron from the second state to a higher one, and last those in which it starts from a stage on the third level. Since at the spot temperature the atoms are less stirred up and more of them in proportion should have electrons at the lower level and fewer at the higher levels, all this is in beautiful agreement with theory.

Zinc—to take one more instance—is much harder to ionize, and its observable lines (which belong to subordinate series) are much weakened in the spots, as they should be.

The ionization potentials have so far been directly determined only for the more volatile metals. Here we may add a good deal to our knowledge by a study of the results obtained from the great laboratory of the sun-spot. From their spectroscopic behavior alone we can arrange a number of elements in a series corresponding to increasing difficulty of excitation of the spectra and doubtless to increasing ionization potentials. Beginning with potassium, we come to calcium, then scandium: next titanium and vanadium, very much alike; then another pair of twins (?), chromium and manganese, with iron the merest step beyond: later, cobalt and nickel: then zinc, and lastly silicon and oxygen.

Now it cannot be a matter of chance that the eleven elements from potassium to zinc are arranged in the order of their atomic numbers altho the list was based on spectroscopic data alone. These eleven elements have increasing numbers of electrons in the outer shell of the atoms—from one upwards—and it is clear that the more electrons there are in this incomplete outer shell, the harder it is to get one out. The position of the elements at the end of the list, as well as of some others like sodium which was not mentioned, can be explained if we assume that, for the same number of electrons in the outer shell, it is easier to get one out, the greater the number of complete shells which intervene between the outer layer and the nucleus. Thus we have added to our knowledge of the properties of matter by observations upon the Sun.

This is but a single illustration of the immense possibilities of the new field of investigation which opens up before us. A vast deal of work must be done before it is even prospected—much less worked out, and the astronomer, the physicist, and the chemist must combine in the attack, bringing all their resources to bear upon this great problem, which is of equal importance to all. We hope to do a good deal more with this at Mount Wilson, and Dr. Millikan and Dr. Noyes may get into the same game at the California Institute of Technology—but there will be room and to spare for all who care to work. It is not too bold to hope that, within a few years, science may find itself in possession of a rational theory of stellar spectra, and, at the same time, of much additional knowledge concerning the constitution of atoms.

The same principles are of great value in interpreting the spectra of the stars. For example, the whitest stars, like those in *Orion*, show the lines of hydrogen, helium, oxygen and nitrogen, but very few metallic lines. Should we therefore conclude that these stars are composed mainly of the permanent gases, with very small quantities of the metals, and that their composition differs radically from that of the Sun, where the metallic lines are strong and those of the gases (except hydrogen) are faint or absent? By no means, for there is abundant evidence that the white stars, even at the surface, are much hotter than the Sun. At such high temperatures the metallic vapors must be completely ionized,—so that there are no neutral atoms left to absorb the arc lines, while most of their atoms have lost two electrons, and are no longer in a position to give even the enhanced lines. The permanent gases, however, are much harder to ionize, and their atoms are therefore in the singly ionized or neutral states, so that they may be recognized in the spectrum—oxygen and nitrogen by their enhanced lines, and helium, which has the highest known ionization potential, by the lines of the neutral atom. At the relatively low temperature of the Sun, the excitation is not great enough to stimulate absorption of the subordinate series of helium (which alone lie in the visible spectrum) and is barely sufficient to do so for oxygen, while hydrogen, which is easier to ionize, gives strong lines. Such considerations not only explain these apparent difficulties: they open up a new way of determining the surface temperatures of the stars, which Saha has already used effectively.

We have two other ways of getting at the temperatures; by a study of their colors,—the red stars being the coolest, and the white the hottest,—and from their surface brightness,—the amount of light given out per square inch. Both methods of measuring temperature are habitually employed in optical pyrometers in industrial practice. The one depending on color has been applied to the stars by several investigations during the past twenty years, with fairly concordant results. The surface-brightness method has just been made applicable to the stars by the measures of stellar diameters with Michelson's interferometer, and may prove important in the future. The results of all three methods are in as good agreement as could reasonably be expected.

It has long been recognized that stars of different temperatures represent different stages of evolution. It now appears very probable that a star starts its recognizable independent life as a great mass of gas of large diameter, low density and relatively low temperature. In the course of ages it contracts; and, so long as the density remains low, it is easy to show,—as Lane did fifty years ago—that it must grow hotter, in order to remain in equilibrium under the steadily increasing gravitational pressure. But when the density becomes fairly high, the gases which compose the star are harder to compress, and an ever smaller rise of temperature suffices to meet the increase of pressure, until at length the rise ceases, and a slow process of cooling begins, which, tho retarded by further shrinkage of the mass, must continue till the star cools down completely, and ends as a dark body. From the known properties of the metallic vapors which compose the main mass of a star, it can be shown that the maximum temperature, inside as well as outside, should be attained when the mean density is not far from one-tenth that of water,—and the observed data show that the white stars, which are the hottest, are much alike in density, and on the average, come close to this theoretical value. Our Sun is denser than water, and is evidently pretty well advanced in the process of cooling. It was probably once ten times brighter than at present, and very likely more.

So far, we have talked almost entirely about the surface of a star. What happens in its interior? Here we can learn nothing by direct observation, and must depend upon inference—and hence once more on our knowledge of the properties of matter. As Eddington,—who has done more than any other man to solve this problem—says, we must devise some sort of "analytical boring machine" to enable us to penetrate the depths. We find at once that the interior of a star must be enormously hot,—the temperature running into the millions of degrees. Can we attempt with safety to predict what would happen to ordinary atoms under such extraordinarily violent abuse?

What would be left of them?

Our confidence in our answer depends on the fact that in the laboratory we can treat individual atoms very roughly indeed. In an X-ray tube, for example, electrons fall thru tens of thousands of volts, and acquire enormous velocities before they hit the target. Being so tiny, they hit individual atoms of the target, and these atoms receive blows as powerful as would result from the collisions between atoms in a gas at a temperature of many millions of degrees. Such atoms are badly shaken up, and respond by the emission of X-rays: but it is well known that these X-rays are characteristic of the kind of atom which is hit. Hence we can be sure that, even under this extreme disturbance, the atoms retain their individuality and are not utterly shattered.

This illustrates a great advantage of our laboratory operations. In the vacuum tube we work,—so to speak,—by retail, acting on only one atom out of many millions (or often billions) of those which are present, while Nature, in the stars, works by wholesale, acting on all the atoms of the gas,—not exactly to the same extent, but very much to the same degree. We can, therefore, study the effects of very violent atomic disturbances, without being obliged to feed so much energy into our apparatus as to endanger the experimenter, or demand impracticable size and cost.

From such studies, we conclude that, in a gas at a temperature of a few million degrees, the lighter atoms would lose all their electrons and be reduced to bare nuclei. But heavier atoms (starting probably somewhere near potassium in the series) would retain a few of the innermost electrons, and the heaviest nuclei, such as those of lead, would probably keep enough electrons attached to them to form a couple of complete shells. Meanwhile the free electrons detached from the atoms would fly about at high speed, colliding with one another and with the remaining nuclei or atomic residues. Could we dip out a sample of matter in this remarkable state, and allow it to cool, the forces of attraction between the nuclei and atoms would gradually resume their sway as the collisions became less violent. Each nucleus would automatically reclothe itself with its ordinary armor of successive shells of electrons, and, at the end, we would find the familiar atoms reconstituted with their usual properties.

But something else happens in the hot interior. The continual violent jostling of the electrons gives rise to an enormous amount of radiation—analogous in nature to light, but most of it of such short wave-length as to resemble "soft" X-rays. This radiation flies about,—emitted by one atom and absorbed by another before it can get very far,—and, in its efforts to escape, exerts an outward pressure. This radiation pressure, under ordinary circumstances, is a very minute force,—for example, in full sunlight it amounts to three pounds per square mile. But, inside of a star, it may rise to thousands of tons per square inch, and become a very important factor in the general equilibrium. Eddington was the first to point this out, and to show that it would become important only in very large masses.

To paraphrase an illustration of his, suppose that we had a series of spheres of gas, each resting in equilibrium under its own gravitation, but of increasing sizes, the first containing ten grams of gas, the next a hundred, the third a thousand, and each following one ten times the mass of the last. Up to number thirty or thirty-one of this series, the internal temperatures will be such that the radiation pressure is insignificant in comparison with the ordinary gas-pressure. But beyond this things change, and for sphere number 35, and all which follow, the radiation pressure in the interior will have increased so much that it counterbalances nearly the whole of the weight of the overlying masses, leaving but a small fraction for the gas pressure to equilibrate. If we drew a curve representing, the relative importance of the radiation pressure we would find it running flat, at practically zero, up to sphere number 31, rising steeply to almost 100 per cent at number 35, and then continuing at this level.

From general physical considerations, we would expect something to happen in the region corresponding to the steep part of the curve,—and as Eddington says, "What happens is the Stars." The masses of all the stars we know about lie between the amounts corresponding to spheres 32 and 35. This is no accident. It is only when the radiation pressure in the interior is a perceptible fraction of the whole pressure that enough radiant energy leaks out to the surface to keep the mass shining as a star. Hence smaller masses, tho, for all we know, they may be abundant in space, are invisible. A very large mass, 100 times or more that of the Sun, would shine brilliantly. But the balance between the radiation pressure inside it and the weight of the overlying layers would be so delicate that a small disturbance would probably tend to break it up. Hence the masses that are left shining, all contain about the same quantity of matter.

The constants which enter into Eddington's equation, from which these results have been deduced, are the very most fundamental which we know; the constant of gravitation, the mass of the hydrogen atom, the velocity of light, and the "quantum". We may therefore say that the masses of the stars, and hence their other properties, which depend on the masses, are predetermined by the most general properties, not even of atoms, but of the structural units out of which atoms themselves are built.

So far, we have for the most part used the stars to illustrate known properties of matter. But, within very recent years, we have come upon evidence that the stars may reveal to us the existence of properties of matter which might otherwise remain unknown.

Every one of the millions of visible stars is radiating energy at an enormous rate,—and this energy is flying off into space quite beyond the power of our present knowledge to follow. We do not know where it goes: but it seems certain that it is not being fed back into the stars again. The stars are losing energy, and have been doing so as long as they have shone. Now this is an exceedingly long time. Take the Sun as an example. It must have been supplying heat to the Earth during the whole of geological time at very much the same rate as at present. If for any single year since life existed on the Earth the Sun had been fifty per cent hotter than it is now, all the oceans would have been heated to the boiling point, and all terrestrial life destroyed. If for a single century the Sun had been fifty per cent cooler, the whole surface of the Earth would have been ice-clad, and life must have perished. The obvious continuity of the evolutionary record shows that no fluctuations at all approaching these can have occurred since Pre-Cambrian times. According to the best available evidence,—based on radio-active data—this interval in the Earth's history may be estimated as of the order of a thousand million years.

The time during which the Sun has been shining must be much longer, for the billion years of which we just spoke cover but a small part of the time of its descent from its maximum brightness to its present state. During its life, therefore, the Sun must have radiated away into space an almost unimaginable amount of energy,—and this energy, so far as we can see, can only have been drawn from some internal source. The greatest known store of energy which the Sun can have utilized is that set free by gravitational action during its contraction from a large size to its present dimensions: but this is only enough to account for something like twenty million years output at the present rate.

We are therefore driven to conclude that there must be some vast internal store of energy in the Sun of a nature previously unknown, but capable of being converted slowly into heat, and so enabling the Sun to keep on shining for something like a thousand times as long as the old hypotheses of gravitational contraction would permit. Eddington has shown that the behavior of the variable stars of the Cepheid type,—which are "giants" a thousand times brighter than the Sun, demands the same conclusion with respect to them.

What may we learn about this unsuspected store of energy?

It must be liberated only in very hot matter,—for otherwise the Earth would be so hot inside that the surface would be red-hot at least. We may conclude roughly that the "unknown process" becomes active only at a temperature of a million degrees or more. But how is it that the rate of liberation of heat in each star is so perfectly adjusted to the rate at which heat can escape by radiation from its surface? An automatic regulation appears to be afforded by Lane's Law, of which we have already spoken. If too much heat is liberated inside a star, the star will have to expand. Its interior will then grow cooler, and this will cut off the over-supply of heat. If too little heat is liberated, the reverse process will take place. We may thus account for the long life and stability of the stars, if we are ready to believe that some enormous store of energy exists in ordinary matter.

So great an amount of energy can hardly be looked for anywhere but inside the very nuclei of atoms: and from radio-activity we know that the heavier nuclei actually contain enormous stores of energy. But something more than ordinary radio-activity is needed.

Within a year or so after these conclusions had been drawn from astrophysical data, a great light was thrown upon the matter from the side of atomic physics.

Dr. Aston, at Cambridge, following and extending the work of Sir J. J. Thomson, has developed one of the most wonderful contrivances ever built—a machine which sorts atoms.

I have no time to describe it in detail—suffice to say that, in a vacuum tube, positively charged atoms are shot thru electric and magnetic fields so adjusted that atoms of deficient weights (more exactly with deficient ratios of mass to charge) are concentrated at different points on a photographic plate, and produce a "mass-spectrum" showing what kinds of atoms were there. From these plates, using the lines produced by known atoms as standards, Dr. Aston has succeeded in measuring, to one part in a thousand, the real atomic weights of the individual atoms. With one notable exception he finds that these are all whole numbers on the ordinary scale of the chemist, on which oxygen is 16. The exception is hydrogen, for which the chemical value of 1.008 is confirmed. In other cases where the chemists have found an atomic weight that was not an even number (such as chlorine) Aston finds that there are two or more kinds of atoms (isotopes) of the same chemical properties, but different atomic weights (all of them, however, whole numbers).

All this confirms the old and half-forgotten opinion that the atoms—even their nuclei, which contain practically all the mass,—are built up out of simpler units. But it seems strange that the hydrogen nucleus, which is the lightest of all, and might well be the unit out of which the rest were built, is the only one which does not fall into the scheme.

Take for example the next lightest element, helium. The helium nucleus, or alpha-particle,—has a positive charge just twice that of the hydrogen nucleus, or the proton, as Aston calls it. But its mass is 3.999 while that of the proton is 1.008.

If we could in some way combine four protons and two electrons, we would get a net resulting positive charge exactly equal to that of the alpha-particle. But the mass of the mixture would be 4.033 (the electrons contributing only 0.001). How can the difference be explained?

Our help comes from relativity in its more general form. According to this, energy has mass—in fact, the two are identical in nature. If we took 4.033 grams of protons and electrons, and subtracted 34 milligrams of energy, we would get our 3.999 grams of alpha-particles. To undo our work, we would have to put the same amount of energy back again.

Now 34 milligrams of energy is a tremendous lot,—enough to heat 7400 tons of water from freezing to boiling. Put in another way, the energy that would be liberated in turning a gram of hydrogen into helium is about five million times as great as that which would be produced by burning this hydrogen in oxygen.

The formation of any other element from hydrogen would liberate nearly the same amount of energy. A similar transformation, taking place thruout the whole mass of the Sun, would suffice to keep it shining at the present rate for about 100 billion years. If then we may believe that, in the intensely heated interiors of the stars, atoms of hydrogen are in some way, as yet unknown, being taken apart, and the pieces built up into the nuclei of other atoms, there will be enough energy liberated as a by-product of this process to keep the stars shining for many billions of years. This is of course a highly speculative idea; but it illustrates how we may very probably in the future obtain information regarding the properties of matter from the stars, which we could secure in no other way.

Even with our present knowledge, we could go a long way toward working out the characteristics of the stars, if we lived on a permanently cloudy planet, and had never seen one.

From what we know now, we could show that only the larger masses of matter (comparable with the actual Sun) would shine. We would know that such bodies would clothe themselves in atmospheres of metallic vapors, and that their light would show a spectrum crossed by dark lines,—and we could tell, too, of what color the light of stars of different temperature would be, and what, in a general way, would be, the lines which would be prominent in the spectra of each class. Indeed, it is hardly too bold to say, even in the present limited state of physical science, that given what we already know of the properties of matter, we might sit down to reason and deduce the stars.

Princeton University Observatory
1921, September 30.